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Feasibility of hydrophobized PES membrane in hybrid MD/FO process using magnetic draw solution

Setareh Salehi, Mohsen Jahanshahi, and Majid Peyravi†

Department of Chemical Engineering, Babol Noshirvani University of Technology,
Shariati Ave., Babol, Iran, Post Code: 47148-71167

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Abstract−The feasibility of PES membrane with hydrophobic property, high glass transition temperature, excellent thermal and chemical stability, with good mechanical properties as porous polymeric support was studied in membrane distillation (MD) process. Several strategies were considered and investigated to decrease membrane wetting by keeping up salt rejection and also to improve the permeate flux of PES membrane in the MD process. From this point of view, hydrophobic PMHS polymer with different concentrations was used as a surface coating solution. The morphology and structure of prepared membranes were evaluated by AFM and FESEM analyses. After coating modification, the salt rejection was increased up to 98% and the contact angle was changed from 65.11° to >100.2°. To increase the water flux, the effect of feed temperature (55 °C and 75 °C) and draw solution utilization containing magnetic nanoparticle (Fe_3O_4) was investigated. Using draw solution provided a driving force from feed solution to permeate side and increased average permeate flux from 2.9 kg/m^2·h to 6.9 kg/m^2·h in the 0.06 g/l of draw solute concentration. It improved permeate flux and salt rejection simultaneously.

Keywords: Membrane Distillation, PES Membrane Modification, PMHS Polymer, Osmotic Pressure, Draw Solution

INTRODUCTION

Membrane distillation (MD) is a membrane processes with a great potential for producing distilled water from seawater [1]. The main challenging issue in MD rather than other membrane processes is the low permeability of water vapor where it can be passed across a membrane thickness due to the thermal difference as a driving force of desalination technique between feed and permeate sides [2,3]. The main requirements for MD are hydrophobicity, nanometer to few micrometers range of pore size, as high as possible porosity, and liquid entry pressure (LEP) to overcome pore wetting. These parameters are dependent on the nature and structural properties of a membrane that is postulated to be used in the MD process [4-7]. On the other hand, operational conditions such as a thermal difference and the reverse flow from pure cold water to the hot stream as a result of the higher concentration of salt in the hot feed solution are affected by the lowering permeability of water vapor. The MD process should satisfy both membrane features and operational conditions simultaneously.

To increase the surface hydrophobicity as well as a decrease in surface energy and control the wettability, the membrane surface has been covered by a hydrophobic layer or functionalized by a hydrophobic agent [8]. McCutcheon et al. reported a superhydrophobic PET fabric that was coated in PVDF/PDMS solution via a nonsolvent induced phase-inversion process. The fabricated superhydrophobic PES fabrics displayed excellent UV resistance and PH stability, laundering durability, self-cleaning property, and wear-resistance [9]. Han et al. employed a new scheme to improve water permeability and salt rejection of thin-film composite (TFC) forward osmosis (FO) membranes by polydopamine (PDA) interfacial polymerized on the surface-functionalized porous polymeric substrates. The obtained value of J_w/J_s for the modified membrane was about 20 l/g by using 2 M NaCl as the draw solution and deionized water as the feed solution at 23 °C [10]. In the current research, polymethyl-hydrosiloxane (PMHS) as a hydrophobic polymer was used to be deposited upon polyethersulfone (PES) ultrafiltration membrane as an additional protective layer. PES with high glass transition temperature, excellent thermal, chemical stability, and good mechanical properties has been used for the fabrication of porous polymeric support [11]. The PMHS/ethanol mixture can be considered as a surface coating solution for PES membranes because PMHS can be dissolved in ethanol, while PES membrane is resistant against the ethanol [7]. Note that the prepared coated membrane should have as high porosity, uniform pore size distribution, and low thickness possible as to achieve a high permeate flux in the MD process.

In the case of the operational condition of the MD process that needs to be improved, the use of nanoparticles in the cold stream can balance the osmotic pressure resulting from the high concentration of salt in the hot stream. This approach has been raised by the forward osmosis (FO) process. In FO, the draw solution with high osmotic pressure was used to pass the water molecule from feed water to draw solution side due to the osmotic pressure difference between feed water sources and draw solution [12-15]. Na et al. reported the use of citrate-coated magnetic nanoparticles (MNPs) by coprecipitation under different preparation conditions as draw

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† To whom correspondence should be addressed.

E-mail: majidpeyravi@nit.ac.ir

solutes for the forward osmosis (FO) process. The water flux of cit-MNP was tested using an unmodified and the modified FO module with magnetic draw solute, respectively. The results confirmed that the modified FO module exhibited higher water flux (17.3 LMH) than an unmodified FO module [16]. Against FO process, the water molecule tends to pass through the membrane from a hot saline stream to cold pure water due to the difference in vapor pressure. However, the higher osmotic pressure of hot saline water causes to pass a water molecule from pure cold water to the hot side to rectify the difference in osmotic pressure. This leads to the water permeation from the cold side to the hot one in the MD process and decreases the water permeation.

In the present work, a feasibility study was performed to find a way for using PES membrane in MD process because of its wettability. Here, two strategies were employed and investigated to decrease membrane wetting by keeping up salt rejection and also to improve the permeate flux of PES membrane in the MD process. To the best of the authors' knowledge, no studies have been reported to use hydrophobic PMHS polymer for PES membrane coating to control its wettability. Further, magnetic particles were used in the cold stream as a new strategy in MD process to overcome the osmotic pressure raised by the high salt concentration in the hot stream, which causes the reverse flow from pure cold water to the hot stream. The presence of MNPs as an osmotic agent provides a high osmotic activity to maintain a lower vapor pressure and decreases the osmotic pressure difference.

MATERIALS AND METHODS

1. Materials

Dimethylformamide (DMF) and Ethanol (C_2H_6O, 99%) were purchased from the Scharlu company. Polyethersulfone (PES, 232.2 g/mol), Polymethylhydrosiloxane (PMHS, Sigma Aldrich), Iron oxide nanoparticle (Fe_3O_4 Merck 50-100 nm particle size nano powder), and Lithium Chloride (LiCl, Merck) were prepared and used as received.

2. Methods

2-1. Membrane Preparation and Hydrophobization

In this work, the used membranes were first prepared via phase inversion method [17] by an ordinary immersion precipitation process and then were hydrophobized by surface coating modification. The components of the casting solution were fixed in all the membranes. In the casting solution, base polymer (PES, 16 wt%), lithium chloride (LiCl, 3 wt%) as a pore former, and DMF (81 wt%) were mixed under constant stirring at 25 °C overnight (the polymer and pore former concentration were optimized in our previous works [7,8]. The degassed solution was poured on a smooth glass plate and cast by doctor blade with uniform speed and a thickness of 100 μm. After casting, membranes were immersed into a coagulation bath containing water and then were dried at room temperature for a short time because membrane without support layer (i.e., polyester) may be wrinkled at long time vaporization and drying.

To deal with the hydrophobic process, the prepared PES membrane was immersed in the coating solution, which was composed of 0.5, 2, and 5 wt% PMHS in ethanol as a solvent. The schematic diagram of the membrane preparation and hydrophobization is illustrated in Fig. S1.

3. Membrane Characterization

Field emission scanning electron microscope (FESEM, TESCAN-15KV) was used for membrane surface, the bottom surface, and cross-sectional morphology investigation. In addition, atomic force microscopy (AFM, model: Easy scan 2 flex) was also employed for surface topology and surface roughness. Contact angle meter (OCA20, Dataphysics, Germany) was utilized to evaluate the membrane hydrophobicity.

Pores are defined by their accessibility to the surface of the material. A closed pore is inaccessible to its surfaces; a blind pore is accessible from the surface but does not travel completely from the upstream to the downstream surface, while a through pore travels from the upstream surface to the downstream surface of a material. The membrane porosity (defined as the pores volume divided by the total volume of membrane) was determined by the gravitational method. An area of 2 cm×2 cm of dried membrane sample was cut and immersed in water for 30 min. The weights of membrane before and after immersing (i.e., after water saturation) were measured; as a result, the membrane porosity was calculated using the following equation:

$$\varepsilon=\frac{(w_1-w_2)/\rho_E}{(w_1-w_2)/\rho_E+w_2/\rho_P}\times 100 \tag{1}$$

where ρ_E and ρ_P represent the density of water (1 gcm^{-3}) and PVDF (1.78 gcm^{-3}) polymer, respectively. w_1 and w_2 are weights (g) of the moistened membrane with ethanol and dry membrane, respectively [5,18].

The membrane tortuosity is another important property of the membrane structure that depends on the shape of voids in the scaffold and reflects the length of the average pore compared to the membrane thickness. A tortuosity value of one is considered for simple cylindrical pores. It represents that the average length of the pore is equal to the membrane thickness. For pores that usually have a more meandering path through the membrane, the tortuosity is larger than one. The membrane tortuosity was acquired by the following correlation:

$$\tau=\frac{(2-\varepsilon)^2}{\varepsilon} \tag{2}$$

Liquid entry pressure (LEP, wetting pressure), which is a significant characteristic of the MD membrane, was determined by a dead-end filtration set-up where a membrane sample was secured in the bottom of the system. The nitrogen gas was changed from the upper to the membrane by a nitrogen gas cylinder and distilled (DI) water was filled as a feed to set up. To determine LEP, the pressure was increased step-wise (0.5 bar for 5 min), when the first drop of DI water came out at the bottom of the membrane sample, that the represented pressure was LEP of the membrane. All characteristic analyses were taken at least three times [19,20].

4. Membrane Performance in MD Process

The performance of as-prepared membranes with the approximate contact area of 30.4 cm^2 was evaluated with an experimental set-up (Fig. S2). Two streams, feed (seawater) and permeate (distilled water) stream, flowed from the upper to the bottom of the MD membrane by two pumps with a flow rate of 400 min/ml and 200 min/ml, respectively [21,22]. The effect of feed side flow rate was more than permeate side on the water permeate flux; therefore, the feed flow rate was considered higher than permeate flow rate. The feed and permeate temperature were constant during all long-term tests (6 h, 75 °C and 25 °C respectively) by two oil and ice baths which were monitored using two thermocouples [23,24]. Other experimental conditions were the same as other short time conditions. The feed and permeate concentration were determined by portable conductivity meter, and also magnetic nanoparticle (Fe_3O_4) concentration as a draw solution was considered 0.02, 0.04, and 0.06 g/l. The MD permeate flux (J) and salt rejection (SR) were calculated according to Eqs. (3) and (4) where J shows the water permeate flux (kg/m^{2}h), m is the permeate weight (kg), A is effective membrane surface area (m^2), t is the sampling time, SR is salt rejection (%), C_p and C_f are weights (kg) of permeate and feed, respectively.

$$J=\frac{m}{A\times t} \tag{3}$$

$$SR=1-\frac{C_p}{C_f}\times 100 \tag{4}$$

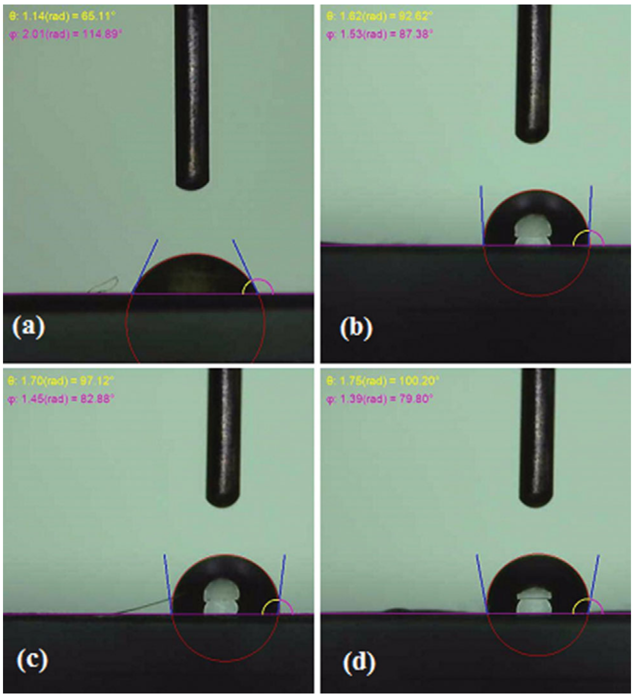

Fig. 1. The contact angle of pure PES (a), PES+0.5 wt% polymer (b), PES+2 wt% polymer (c), PES+5 wt% polymer (d).

RESULTS AND DISCUSSION

1. LEP, Contact Angle, Porosity, and Tortuosity

The hydrophobicity of the membrane is the most crucial aspect of the MD system, which means only water vapor is allowed to transport through the membrane pores. If the liquid penetrates the pores, a wetting phenomenon occurs. This decreases the permeability due to the blocked pores and changes the selectivity of the membrane. To prevent the wetting phenomenon, the applied hydrostatic pressure to a membrane must be lower than LEP (minimum requirement pressure to overcome membrane wetting). High LEP can be achieved using a hydrophobic membrane material as well as small pore size, narrow pore size distribution, and ideal cylindrical pore geometry. High permeate flux in membrane distillation can be connected to membrane porosity because high porosity makes a bigger surface area for evaporation, which leads to greater amount of vapor molecules penetrating through membrane pores; and as a result, permeate flux is increased [25-27]. The contact angle (CA), porosity (ε), LEP, and tortuosity of pure PES and hydrophobic PES membrane were determined and summarized in Table 1 and Fig. 1. Generally, the porosity of a membrane in the MD process is usually ranging from 30 to 85% [5]. All prepared membranes showed porosity between 55-65%, which was in the range of MD membrane. This was returned to the presence of LiCl as pore former in the casting solution which was reported in our previous study [28]. It seems that the additional hydrophobic layer coated upon PES membrane had a positive effect on increasing the modified membranes (0.5 wt% and 2 wt%) porosity and the value of them was increased from 56.3% (pure PES) to 65% and 61.5% (0.5 wt% and 2 wt%, respectively), but increasing of hydrophobic layer concentration had no considerable effect on increasing of 5 wt% modified membrane porosity. It can be related to when the concentration PMHS was increased, the viscosity of the coating solution was visually increased, whereas it is rational to deposit gradually thicker and denser layer upon PES membrane surface [29]. On the other hand, the presence of polymer solution on the top membrane surface helped in constricting the gap on the surface, so it resulted to penetrate within the pore and deposit upon the pore wall. This leads to being smaller pore sizes compared to its bulk of membrane. It should be noted that the smaller pore sizes of the membrane can increase the LEP value. As can be seen, LEP and contact angle parameters were increased by an increment of polymer (PMHS) concentration in the coating solution. The nature of polymer PMHS as it contains silane groups is hydrophobic [6], so contact angle parameter of modified membranes compared to the

Table 1. The values of contact angle, porosity, LEP, tortuosity of pure PES, and surface coated PES membrane

Membrane	Contact angle (°)	LEP (bar)	Porosity (%)	Tortuosity
Pure PES	65.11±3	1±0.02	56.3±0.75	3.6±0.02
PES+0.5 wt% polymer	92.62±1	1.5±0.15	65±1	2.8±0.08
PES+2 wt% polymer	97.12±2	4.5±0.25	61.5±0.95	3.1±0.08
PES+5 wt% polymer	100.2±5	>5.5±0.3	56±1	3.7±0.12

Table 2. The surface roughness of pure PES and modified membranes

Membrane	R_a (nm)	R_q (nm)	R_{max} (nm)
Pure PES	11.3	14.3	79.6
M0.5 wt%	13.6	19	105.6
M2 wt%	32.4	41.2	199.9
M5 wt%	13.8	18.8	88.9

pure membrane and also modified membrane containing higher percentage polymer to other was increased. There is a direct relationship between LEP and hydrophobicity because the pores of the membrane surface fill in the hydrophobic polymer, water requires higher pressure (LEP) to penetrate through the membrane pores. The tortuosity as the structural and curvature properties of membrane pores is commonly used to describe diffusion in the porous membrane and the mass transport mechanism. According to Eq. (2), it is related to porosity value inversely. From this point of view, the lower tortuosity value showed low curvature in the pores of membranes and resulted in the higher value of the permeate flux [5].

2. FESEM and AFM Analyses

The membrane morphology was characterized before and after coating by FESEM imaging. Fig. 1 illustrates the surface layer of the pure PES and hydrophobized PES membrane. According to the results of Table 2, the 2 wt% modified membrane has the highest roughness (R_{max}), so it was considered as the most appropriate membrane, and the surface layer was illustrated. It can be firmly concluded that polymers are deposited on the membrane surface. The long length of polymethyl-hydro siloxane polymer is caused to agglomerate after coating on the membrane surface, which is clearly seen in Fig. 2. Furthermore, the increased contact angle from 65.11° to 100.2° after hydrophobization confirms the deposition of hydrophobic PMHS polymer at the top surface layer. The cross-sectional FESEM images of pure and modified membranes at different magnifications are shown in Fig. 3. A finger-like structure as a desirable morphology was obtained for the PES membrane. A comparison between Fig. 3(b) and c indicates that a thin and dense layer with an average thickness of 500 nm was formed on the top of the membrane surface after PMHS coating.

To support the discussions above, AFM analysis was used to measure the membrane surface topology and roughness. As shown in Fig. 4, the surface of the modified PES membrane (0.5-2 and 5 wt%) is visually rougher than the pure PES membrane. The bright beads on the modified membrane surface were attributed to coated polymers which were increased with higher loading of coating solution [30,31]. It seems that these beads caused to create hills and valleys upon the PES membrane after coating by PMHS solution via microscopic inspection, which was consistent with the FESEM images. Also, the higher roughness of the modified PES membrane affected the higher value of contact angle. The average roughness (R_a), root mean square roughness (R_q), and maximum roughness (R_{max}) values are presented in Table 2. Here, the pure PES membrane shows R_{max}=79.6, whereas the $M_{0.5\%}$, $M_{2\%}$ and $M_{5\%}$ represent higher average roughness of 105.6, 199.9, 88.9, respectively. The higher value of roughness is attributed to the presence of PMHS upon the PES membrane.

3. Applicability of PES Membrane in MD

As a main aim of our work, the feasibility of PES membrane for membrane distillation was studied. Generally, the salt rejection in the MD process is near to 100%, which means that the water molecule and its following any salt could not penetrate in the pores of the membrane. This is just due to the permeation of water vapor through the membrane pores. In this work, although the pure PES membrane showed permeate flux higher than the coated membrane, the value of salt rejection was below 85%. It means that the wetting phenomenon happened and liquid feed was passed from hot stream to cold pure water instead of water vapor molecule. In this regard, the pore wettability of the PES membrane was decreased by coating a hydrophobic layer upon the PES layer. Fig. S3 shows that the average permeate flux was decreased after coating PMHS with different concentrations. It was due to mass transfer

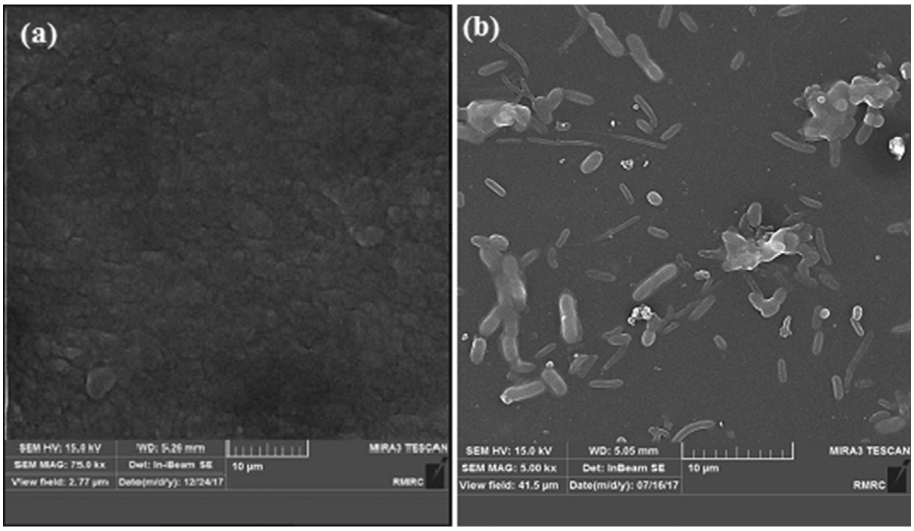

Fig. 2. The surface FESEM image of pure PES membrane (a) hydrophobic PES membrane (2 wt%) (b).

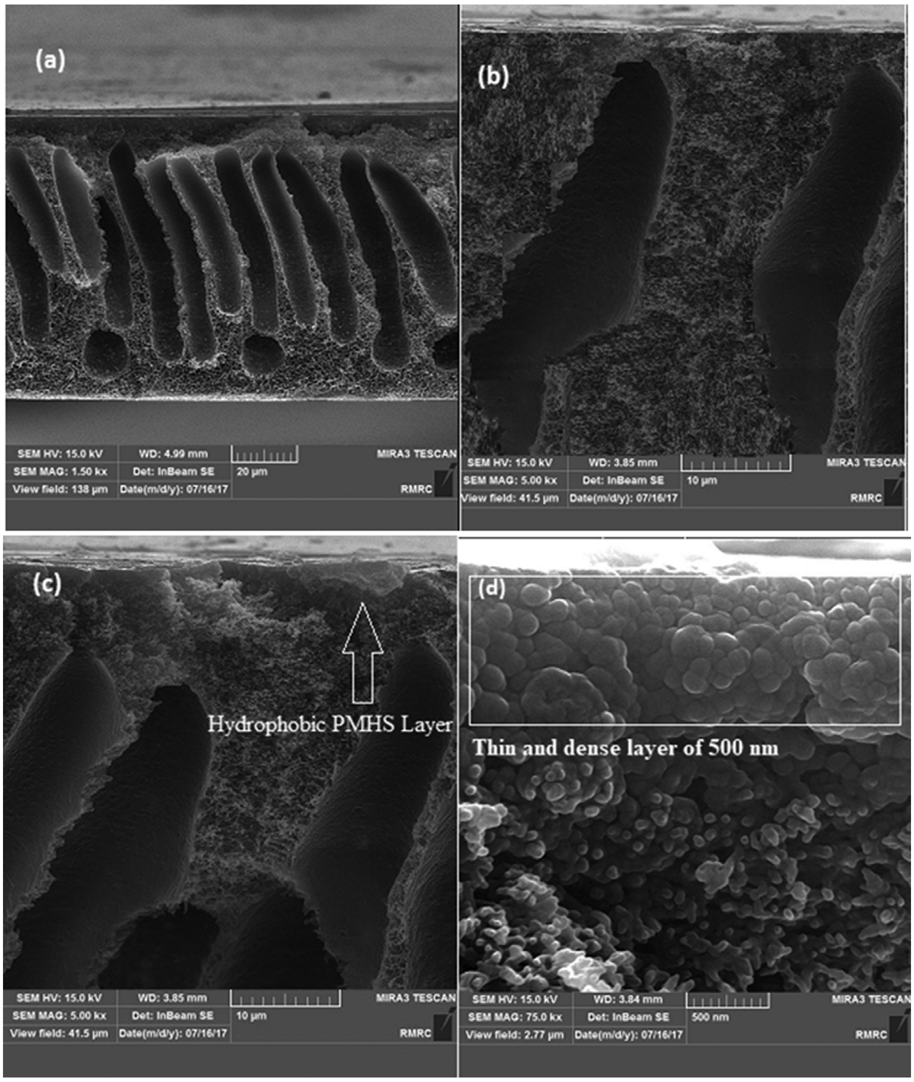

Fig. 3. FESEM images of cross-section of pure PES membrane ((a) and (b)), modified PES membrane ((c) and (d)) at different magnifications.

resistance of the additional coated layer. As shown in Fig. 5, a comparison between the long-term performance of pure PES and coated membranes demonstrates that the salt rejection value increased up to 98% after surface modification due to lack of wetting as a result of the hydrophobic coated layer. Also, the salt rejection of coated PES membrane shows acceptable rejection value in the MD process during desalination over time. However, the salt rejection of pure PES membrane decreased from 85% to 60%. It was attributed to the changes in the membrane pore structure as reported by Manttari et al. that pores increased in diameter with temperature [32]. It seems that a high temperature may permanently reorient the polymer chains in a pure PES membrane due to its less dense polymer structure compared to a PMHS polymer. Fig. 5 shows the salt rejection of coated PES membranes with different PMHS concentrations over time. There was not any significant difference between salt rejection of different coated membranes, and the observed difference was in the permeability. Although coating membrane by PMHS layer has provided the usability of PES membrane in MD process and improved salt rejection significantly, the permeate flux of modified membrane was still low rather than unmodified membrane, which next section has been paid to use the operational technique to increase permeate flux of modified membrane in MD process.

4. Improvement of Operational Condition

In this section, we used two strategies to increase the low permeability of PMHS coated membrane. By change in operational conditions through two routes: (i) an increase in thermal difference and (ii) the creation of reverse flow from pure cold water to the hot stream as a result of the higher concentration of salt in the hot feed solution, it can decrease the lowering rate of water vapor permeability. The MD process should satisfy both membrane features and operational conditions simultaneously.

According to some reported works [33-35], permeate flux in MD can be increased with increasing feed temperature. The maximum temperature that was considered in the MD process is below the boiling point of the feed solution, commonly between 20 °C to 90 °C. According to the Antoine equation, feed temperature and vapor pressure have a direct relationship which leads to vapor pres-

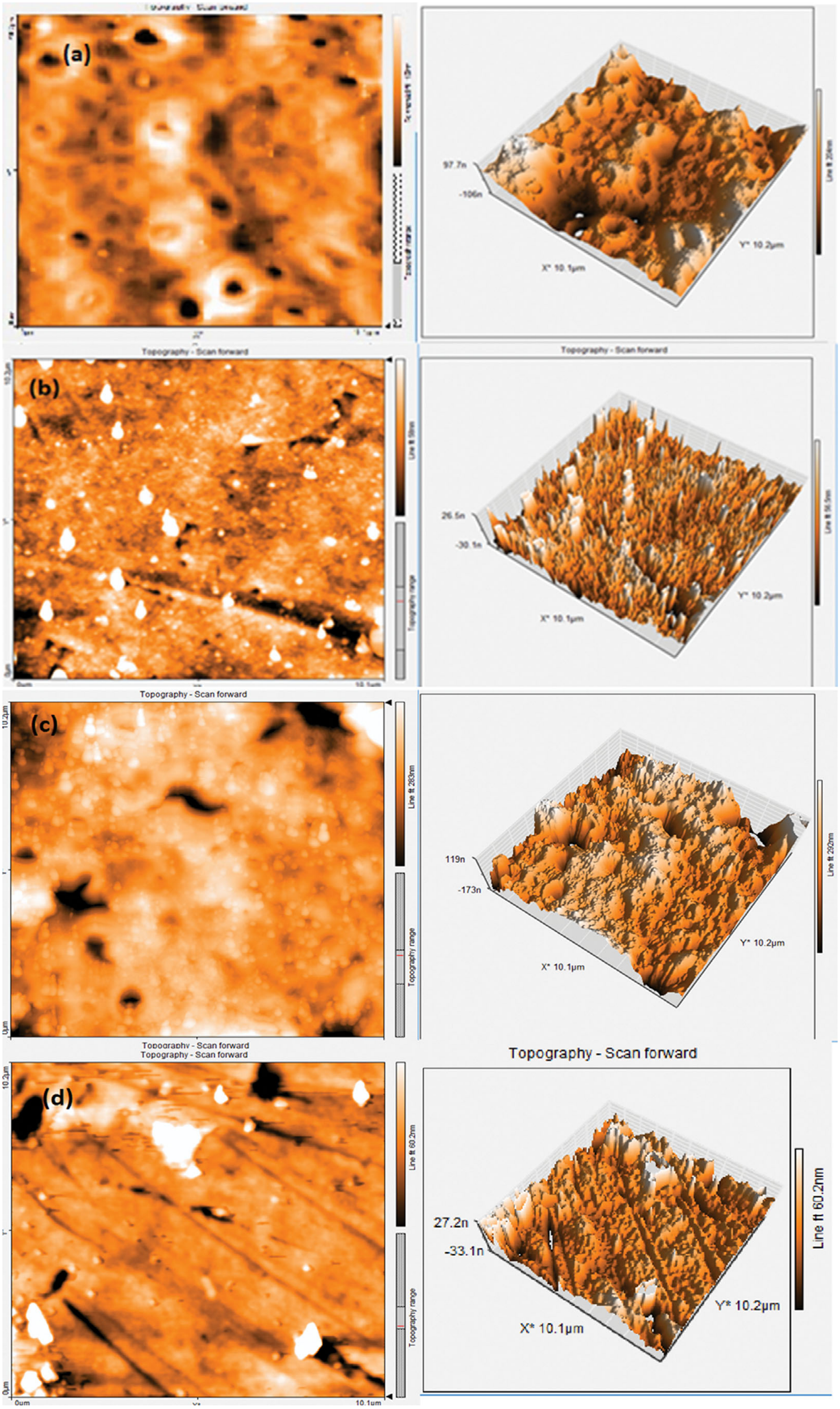

Fig. 4. The AFM images of pure PES membrane (a), membrane 0.5 wt% (b), membrane 2 wt% (c) and membrane 5 wt% (d).

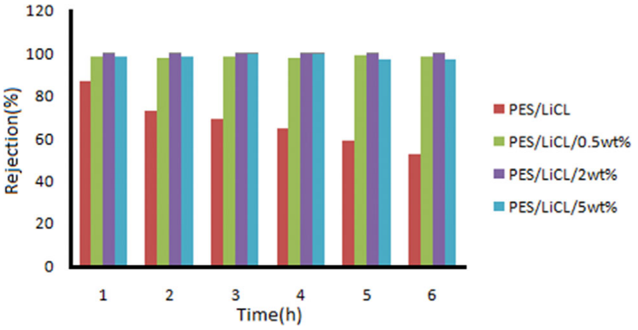

Fig. 5. Comparison of salt rejection value pure and different coated PES membrane.

sure increasing exponentially with feed temperature. So, the feed temperature has an exponential influence on the permeate flux [5, 36]. At the same condition, the effect of hot fluid temperature is more than the cold fluid temperature on the permeate flux, because the difference of vapor pressure at low temperature is low. In Fig. S4, when feed (hot fluid) temperature was increased (increasing from 55 °C to 75 °C), vapor pressure was also increased (0.155 to 0.38 atm). It increased the driving force and resulted in flux enhancement. It must be pointed out that increasing feed temperature does not affect salt rejection [4,37,38].

In addition to increasing vapor pressure difference, the control of reverse flow from cold stream to hot feed water has been considered here. As defined, a water vapor molecule from hot feedwater passes through the membrane pores to pure cold water due to the temperature difference between hot and cold water. In contrast, a reverse flow from cold pure water tends to pass to hot feed water due to the higher concentration of feed water. This acts as an osmotic driving force similar to what occurred in the forward osmosis process. By using magnetic nanoparticles (MNPs) in cold water streams can increase the osmotic pressure of cold streams and decrease the osmotic pressure difference between hot and cold stream. This limits the reverse flow from cold streams to hot feed line (from draw solution to feed solution). MNPs were used as a typical magnetic material so that they can be easily and effectively separated from the permeate by an external magnetic field as shown in Fig. 6. Furthermore, it has low cost, minimal toxicity and can generate a high osmotic pressure to ensure a positive permeate flux [39-41].

Fig. 6. Draw solution (Fe_3O_4 nanoparticle) before and after applied magnetic field.

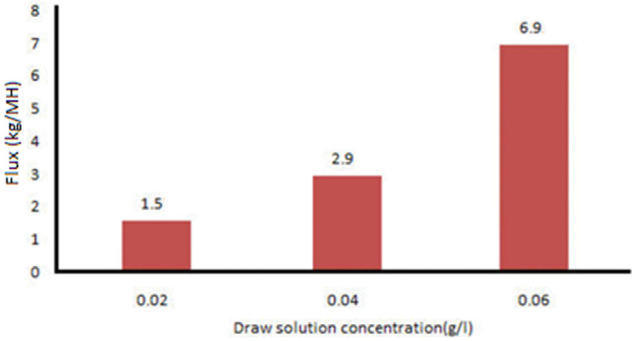

Fig. 7. Effects of draw solution concentration on the average flux of 2 wt% modified membrane.

Fig. 7 shows the flux of coated PES membranes when magnetic nanoparticles were used in the cold stream water as a draw solution. Several concentrations were considered on average for draw solution (0.02, 0.04 and 0.06 g/lit) to select one as a suitable concentration that can increase permeate flux of modified membrane in comparison to without the presence of MNPs. It can be observed that the draw solution has a positive effect on the water permeate flux of modified membrane in the MD process. Comparison of permeate flux in different concentration of draw solution showed that average permeate flux increased from 1.5 kg/m^2·h (0.02 g/l), 2.9 kg/m^2·h (0.04 g/l) to 6.9 kg/m^2·h (0.06 g/l), whereas salt rejection remained up to 99.9%. Although permeate flux of 2 wt% modified membrane from 2.3 kg/m^2·h without draw solution to 2.9 kg/m^2·h with draw solution was increased, but 0.06 g/l and higher concentration of MNPs in draw solution can be suitable concentration, because permeate flux value of modified membrane was more increased from 2.3 kg/m^2·h (2 wt%) without draw solution to 6.9 kg/m^2·h with draw solution. It has resulted from the created osmotic pressure by 0.06 g/l MNPs being sufficient to overcome the osmotic pressure difference due to the high salt concentration in the hot stream. The obtained flux of 2 wt% modified membrane when 0.06 g/l of draw solute concentration was used instead of pure water in the cold stream was higher than the water permeate flux at increased feed temperature (75 °C) at the same operating time. This result shows that applying MNPs in the cold stream can economically improve the MD process at lower working temperature. When the concentration of Fe_3O_4 nanoparticle as a draw solute was increased, the water flux also improved. This can be related to the draw solution with higher concentration which may produce higher osmotic pressure (higher driving force) and lead to higher water flux.

A comparison study between the current work and some literature in which different membrane modifications and operational conditions were utilized to increase permeate flux of MD is presented In Table 3. Salehi et al. [8] and Rastegarpanah et al. [42] used ZnO nanoparticle with silane coupling agent (n-octyltriethoxysilane) and tetraethylorthosilicate (TEOS) and trimethylchlorosilane (TMSCl) as grafting agents, respectively, and permeate flux was increased to 4.7, –13.4 kg/m^2·h in 60 °C, 10.8, –0.8 kg/m^2·h in 80 °C

Table 3. A comparison study between the current work and some literature

MD flux after modification	Type and concentration of cold stream	Type and concentration of hot stream	Feed temperature (°C)	Type of modification	Type of membrane	Reference
In 60 °C, 4.7 and −13.4 $kg/m^2\cdot h$In 80 °C, 10.8 and −0.8 $kg/m^2\cdot h$	Pure water	7 g/l (0.12 M) and 12 g/l (0.2 M) NaCl	60 to 80	ZnO nanoparticle was modified with silane coupling agent (n-octyltriethoxysilane) and coupled by ZIF-8 crystal	PVDF	Salehi et al. [8]
Among the modified membrane (0 to 2%), only the permeate flux of 0.5% modified membrane was up to the pure PVDF membrane. ~20 $kg/m^2\cdot h$	Pure water	NaCl	86	ZnO nanoparticle modified with using 3-aminopropyltriethoxysilane as a coupling agent and lauric acid in order to increase the hydrophobicity of nanoparticle surface	PVDF	Ardeshiri et al. [6]
5.78 $kg/m^2\cdot h$ to 1.8 2 wt% (0.74 M) NaCl	Pure water	2 wt% (0.74 M) NaCl	35 to 50	(PES) membrane is treated by using tetraethylorthosilicate (TEOS) and trimethylchlorosilane (TMSCl) as grafting agents	PES	Rastegarpanah et al. [42]
6.5 $kg/m^2\cdot h$	Pure water	27 wt% (10 M) NaCl	60	hydrophobic/oleophobic coating modification	PES	Eykens et al. [43]
from 2.3 $kg/m^2\cdot h$ (2 wt%) without draw solution to 6.9 $kg/m^2\cdot h$ with draw solution	magnetic nanoparticle (Fe_3O_4, 0.02, 0.04, and 0.06 g/l)	2 M NaCl	55 and 75	hydrophobic PMHS polymer coating modification	PES	The current work

and 5.78 $kg/m^2\cdot h$ to 1.8 $kg/m^2\cdot h$ in an operational time, respectively. In addition to different membrane modifications and operational conditions, a draw solution was used in the current work to overcome the osmotic pressure raised by the high salt concentration in the hot stream, and permeate flux was increased from 2.3 $kg/m^2\cdot h$ (2 wt%) without draw solution to 6.9 $kg/m^2\cdot h$ with draw solution.

CONCLUSION

PES polymeric membrane was prepared by phase inversion method and applied to hydrophobic membrane for MD application. Pure PES membrane was shown to have high permeate flux and low salt rejection; to the feasibility of PES membrane in MD process it was modified by surface coating membrane. After modification, the surface of coated membrane had up to 96% salt rejection, and permeate flux of the 2 wt% membranes was more than the others. The higher concentration of PMHS in coating solution revealed higher contact angle value, 65.11°, 92.62°, 97.12°, and 100.2° are related to pure PES, modified membrane (0.5 wt%, 2 wt%, and 5 wt%), respectively. The feed temperatures considered were 55 °C and 75 °C to investigate its effect on the water permeate flux and reported 2.3 and 5.9 $kg/m^2\cdot h$ in 2 wt%, respectively. Furthermore, adding magnetic nanoparticle (Fe_3O_4) to permeate solution made a driving force that caused the stream to flow permeate side to the feed side; finally, average water permeate flux was increased from 6.9 $kg/m^2\cdot h$ in 0.06 g/l of draw solution.

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SUPPORTING INFORMATION

Additional information as noted in the text. This information is available via the Internet at http://www.springer.com/chemistry/journal/11814.

REFERENCES

1. D. E. Suk, T. Matsuura, H. B. Park and Y. M. Lee, *Desalination*, **300**, 312 (2010).
2. J. Deshpande, K. Nithyanandam and R. Pitchumani, *J. Membr. Sci.*, **523**, 301 (2017).
3. D. Wintera, J. Koschikowskia, F. Grossa, D. Mauchera, D. Düvera, M. Jositza and T. Mannb, *J. Membr. Sci.*, **758**, 771 (2017).
4. N. Shafaei, M. Jahanshahi, M. Peyravi and Q. Najafpour, *Korean J. Chem. Eng.*, **2968**, 2981 (2016).
5. S. Bandehali, F. Parvizian, S. M. Hosseini, T. Matsuura, E. Drioli, J. Shen, A. Moghadassi and A. S. Adeleye, *Chemosphere*, **283**, 131207 (2021).
6. F. Ardeshiri, S. Salehi, M. Peyravi, M. Jahanshahi, A. Amiri and A. Shokuhi Rad, *Asia-Pacific J. Chem. Eng.*, **13**, 3 (2018).

7. F. Ardeshiri, A. Akbari, M. Peyravi and M. Jahanshahi, *Korean J. Chem. Eng.*, **255**, 264 (2019).
8. S. Salehi, M. Jahanshahi and M. Peyravi, *Chem. Eng. Technol.*, **1994**, 2004 (2019).
9. P. Pouresmaeel-Selkjani, M. Jahanshahi and M. Peyravi, *High Performance Polymers*, **759**, 771 (2016).
10. R. R. Darabi, M. Peyravi, M. Jahanshahi and A. A. Q. Amiri, *Korean J. Chem. Eng.*, **2311**, 2324 (2017).
11. M. L. Lind, A. K. Ghosh, A. Jawor, X. Huang, W. Hou, Y. Yang and E. M. V. Hoek, *Langmuir*, **25**, 10139 (2009).
12. Q. Ge, J. Su, T. Sh. Chung and G. Amy, *Am. Chem. Soc.*, **382**, 388 (2011).
13. Q. Ge, M. Ling and T. Sh. Chung, *J. Membr. Sci.*, **225**, 237 (2013).
14. R. R. Darabi, M. Jahanshahi and M. Peyravi, *Chem. Eng. Res. Des.*, **11**, 25 (2018).
15. Y. Xua, X. Peng, Ch. Y. Tangb, Q. Shiang Fud and Sh. Niea, *J. Membr. Sci.*, **298**, 309 (2010).
16. Y. Na, S. Yang and S. Lee, *Desalination*, **34**, 42 (2014).
17. M. Khajouei, M. Peyravi and M. Jahanshahi, *J. Membr. Sci. Res.*, **2**, 12 (2017).
18. A. B. Rostam, M. Peyravi, M. Ghorbani and M. Jahanshahi, *Appl. Surf. Sci.*, **17**, 28 (2018).
19. G. Racz, S. Kerker, Z. Kovacs and G. Vatai, *Chem. Eng.*, **81**, 91 (2014).
20. E. Jannatduost, A. A. Babaluo, F. Abbasi, M. A. Ardestani and M. Peyravi, *Desalination*, **1136**, 1139 (2010).
21. F. Ardeshiri, A. Akbari, M. Peyravi and M. Jahanshahi, *J. Ind. Eng. Chem.*, **74**, 14 (2019).
22. L. D. Tijing, Y. C. Woo, W. G. Shim, T. He, J. S. Choi and S. H. Kim, *J. Membr. Sci.*, **158**, 170 (2016).
23. H. Fan and Y. Peng, *Chem. Eng. Sci.*, **94**, 102 (2012).
24. R. Roshani, F. Ardeshiri, M. Peyravi and M. Jahanshahi, *RSC Adv.*, **23499**, 23515 (2018).
25. R. Dasa, K. Sondhib, S. Majumdara and S. Sarkara, *J. Asian Ceram. Soc.*, **4**, 243 (2016).
26. L. Zheng, Zh. Wu, Y. Wei, Y. Zhang and Y. Yuan, *J. Membr. Sci.*, **71**, 85 (2016).
27. K. J. Lu, J. Zuo and T. ShungChung, *J. Membr. Sci.*, **65**, 75 (2016).
28. F. Esfandian, M. Peyravi, A. A. Qoreyshi and M. Jahanshahi, *J. Membr. Sci. Res.*, **26**, 32 (2016).
29. M. Khajouei, M. Peyravi and M. Jahanshahi, *J. Membr. Sci. Res.*, **2**, 12 (2017).
30. M. Jahanshahi, A. Rahimpour and M. Peyravi, *Desalination*, **29**, 36 (2010).
31. A. Rahimpour and M. Jahanshahi, *Desalination and Water Treatment*, **14013**, 14023 (2016).
32. M. Manttarii, A. Pihlajamski, E. Kaipainen and M. Nystram, *Desalination*, **81**, 86 (2002).
33. T. Y. Cath, V. D. Adams and A. E. Childress, *J. Membr. Sci.*, **5**, 16 (2004).
34. L. M. Diez and M. I. Gonzalez, *J. Membr. Sci.*, **265**, 273 (1999).
35. A. M. Alklaibi and N. Lior, *Desalination*, **111**, 131 (2005).
36. A. Razmjou, E. Arifin, G. Dong, J. Mansouri and V. Chen, *J. Membr. Sci.*, **850**, 863 (2012).
37. W. TaXu, Zh. P. Zhao, M. Liu and K. Ch. Chen, *J. Membr. Sci.*, **110**, 120 (2015).
38. M. Gryta, *Membranes*, **415**, 429 (2012).
39. Z. Shabani and A. Rahimpour, *Iran. Polym. J.*, **25**, 887 (2016).
40. R. Ramezani, M. Peyravi, M. Jahanshahi and S. A. A. Ghoreishi Amiri, *Korean J. Chem. Eng.*, **2311**, 2324 (2017).
41. Q. Ge, L. Yang, J. Cai, W. Xu, Q. Chen and M. Liu, *J. Membr. Sci.*, **520**, 550 (2016).
42. A. Rastegarpanah and H. R. Mortaheb, *Desalination*, **99**, 107 (2016).
43. L. Eykens, K. D. Sitter, L. Stoops, C. Dotremont, L. Pinoy and B. V. Bruggen, *Appl. Polym.*, **1**, 11 (2017).